Solar–Terrestrial Connection: Long-Term and Short-Term Climate Variability

The Earth's CLIMATE expresses the combined response of the atmosphere, the OCEANS and the continents to the energy that is received from the Sun. Any variation in the energy received from the Sun or radiated away from Earth and any change in the distribution of energy over the Earth's surface will therefore have an effect on climate (see also EARTH'S ATMOSPHERE).

By climate we usually understand the average state of the atmosphere over several years. Superposed on that is the large seasonal variation caused by the annual change of the solar zenith angle and the daily variation due to changes in the energy distribution over the Earth caused by the rotation of the Earth around its axis.

The observed climate is a mixture of many different atmospheric processes including a number of complex feedback mechanisms. Some of these processes are directly affected by human activity such as burning of fossil fuel. However, there is also a large natural variability, which it is necessary to understand in order to assess the possible contribution of humanity to climate.

Causes of climate changes

Causes of climate change can be divided into two main categories: those that are due to external forcing of the climate system and those that are due to an internal redistribution of energy and matter within the global climate system.

The internal redistribution has a significant effect on short time scales ranging from years to decades. The most prominent example of the interannual variability in the climate is the El-Niño-Southern oscillation (ENSO). It is due to a complicated interaction between various air masses in the tropics and anomalous warming of the eastern and central tropical Pacific Ocean. The heat capacity of the oceans and the nature of the ocean currents play a major role in controlling the state of the atmosphere and hence the climate. Ocean currents are in general not yet known with sufficient accuracy to enable us to predict their effect on climate. In addition, their effect is probably associated with chaotic behavior that may make it impossible to predict such changes. Indications of the probable range of such variations in a statistical sense may, however, be acquired from numerical climate models.

Changes in the energy budget of the Earth will result in persistent climate changes. The Sun's radiation is the source of the energy that drives the weather and climate. The Sun emits radiation at various frequencies. As a first approximation the Sun radiates energy corresponding to a black body with a temperature of 5770 K, the solar surface temperature. Integrated over all wavelengths the total irradiance from the Sun at the position of the Earth is approximately 1368 W m^{-2}, the solar constant. The cross section exposed to the solar energy corresponds to an area of πR^2 whereas the total surface area of the Earth including the night side is $4\pi R^2$. Distributed evenly over the Earth's surface we therefore need to divide the number by 4 to yield an average power of 342 W m^{-2} at the top of the atmosphere. In a steady state with no climate change the Earth would reradiate the same amount of energy as a black body at the global average temperature, approximately 288 K. This corresponds to a longer wavelength with a peak in the infrared part of the spectrum. The short-wave radiation from the Sun reaching the Earth's surface and the long-wave radiation from Earth to space have to pass through the Earth's atmosphere, which acts like a filter. The effect of the filter depends on the wavelength of the radiation and it has therefore a different effect on the incoming and outgoing radiation. The net effect of these processes, also called the Earth's radiation budget, is therefore highly dependent on the composition of the atmosphere. At present, the composition of the atmosphere is such that it keeps the global temperature about 31 K higher than the Earth would be without an atmosphere. The dominant gases contributing to this warming effect, the natural GREENHOUSE EFFECT, are water vapor and carbon dioxide (CO_2).

The composition of the atmosphere may change for a number of reasons. Volcanic activity is often accompanied by emission of considerable amounts of sulfur in the stratosphere. These emissions create aerosols that reflect sunlight and the effect is therefore a cooling of the Earth. Since the aerosols remain in the atmosphere for several years the effect on the Earth's average surface temperature may be quite significant. Energy balance calculations indicate that volcanic activity may have contributed to the observed global average temperature variations during the past 150 yr. In the stratosphere another gas, ozone (O_3), is varying because of the solar cycle variation in the ultraviolet radiation that produces O_3. However, the ozone layer is also depleted owing to the accumulating amount of anthropogenic chlorofluorocarbons (CFCs). Both CFCs and O_3 are very effective greenhouse gases but their combined effect on climate is significantly reduced because of the destructive effect of CFCs on O_3 (see OZONE HOLE).

Most concern is, however, associated with the effect of the atmospheric concentrations of greenhouse gases such as CO_2 and methane (CH_4). We know that these concentrations have increased considerably over the past 150 yr, after the start of industrialization and the rapid increase of the population of our planet. The gases absorb the long-wave radiation from the Earth's surface and are supposed to be responsible for at least part of the global warming that has characterized this century. The effect of human activity is rather complex, because the burning of fossil fuel that causes the increased concentrations of CO_2 has also caused an increase in the contents of sulfate aerosols in the troposphere. The effect of this may be a cooling similar to the effect of volcanic aerosols. Whereas the production of CO_2 is proportional to the amount of fossil fuel used, the emission of sulfate aerosols may

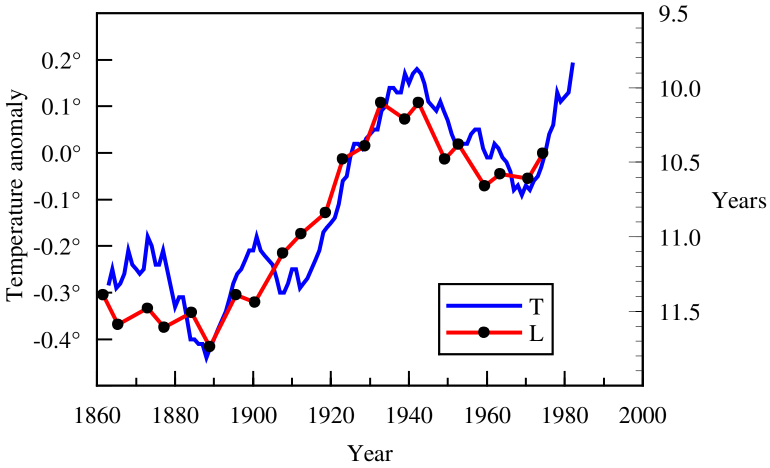

Figure 1. Smoothed length of the solar cycle (L) and the 11 yr running average of the northern hemisphere land temperature (T). (Figure taken from Friis-Christensen E and Lassen K 1991 Length of the solar cycle: an indicator of solar activity closely associated with climate *Science* **254** 698–700.)

be affected considerably by various measures to clean the exhaust, for instance the use of filters. The relative importance of these two atmospheric constituents that are products of fossil fuel burning has therefore changed in time and so has their expected impact on climate.

Long-term changes of climate

On very long time scales, billions of years, we know that the solar luminosity has been increasing monotonically with time. At the time of the formation of the Earth the Sun's output was only 70% of its present output. According to paleoclimatic records this huge change in luminosity has not, however, been associated with an expected corresponding increase in the average temperature of the Earth. This 'faint young Sun' paradox may be explained in several ways. Some of the most plausible ones are related to changes in the atmosphere and its composition. In particular, the large amounts of carbon trapped in carbonate sediments indicate that the abundance of CO_2 in the atmosphere must have been much larger during times in the past. An interesting theory by James Lovelock, called the Gaia hypothesis, even suggests that on very long time scales life itself is capable of modifying the Earth's environment, including the atmosphere, in order to optimize conditions for its own continued existence.

The history of Earth shows that climate has been varying on many time scales. Most prominent during the last two million years has been the repeated occurrence of glaciation with a period of approximately 100 000 yr. Reconstruction of past climate variations shows that, on top of this dominant quasi-cycle, shorter quasi-cycles of roughly 41 000 and 21 000 yr are superimposed. The apparent regularity of this phenomenon and the calculated periods has called for an astronomical explanation that was first quantitatively formulated by MILANKOVITCH in the 1920s. According to the Milankovitch theory the climatic cycles are related to the variations in the received solar energy and in particular its distribution over the Earth's surface. These variations can be predicted by changes in the rotational and orbital parameters of the Earth. The major period of about 100 000 yr is related to the variation of the eccentricity of the Earth's orbit around the Sun. The other parameters are related to the variation of the tilt of the Earth's axis between about 22° and 25° (∼41 000 yr) and the precession of the equinoxes and solstices around the Earth's orbit (∼21 000 yr). Although the changes may seem rather small, they have apparently been sufficient to initiate large oscillations in the Earth's climate in a manner still poorly understood. Model calculations show that the response to the orbital forcing is non-linear and that it involves internal processes and feedback mechanisms. These feedback mechanisms may involve changes in the atmospheric composition, in the amount of snow and ice, and in the biological cycle. It is still an open question, however, whether the external orbital forcing drives the internal processes or whether they act as a pacemaker for the free oscillations in the internally driven system. However, the apparent large climate sensitivity to small changes in the amount and latitudinal distribution of solar radiation has contributed further to the concern of possible effects of a humanly induced enhanced greenhouse effect.

Climate variations on shorter time scales

In addition to these crucial variations in the Earth's climate our records of past climate do show that climate has been varying also on time scales that are too short to be possible manifestations of orbital parameters. Some of these oscillations may be the result of internal oscillations but during the last century there has been an increasing number of scientific reports that indicate that some of them may be attributed to variations in the Sun.

Usually we regard the Sun as just an eternal source of energy that sustains life on Earth. Until recently the energy

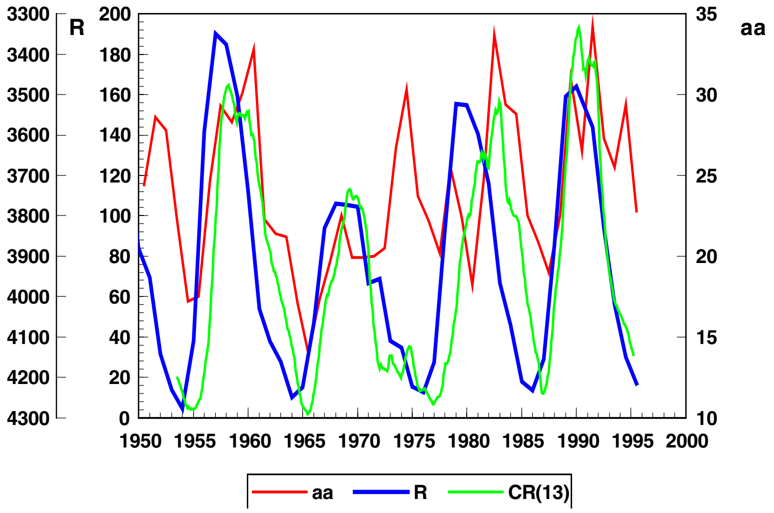

Figure 3. Variation of the cosmic ray flux (CR) observed at Climax station, USA, the yearly sunspot number (R) and the geomagnetic activity index *aa*. Note the reversed scale of the cosmic ray flux.

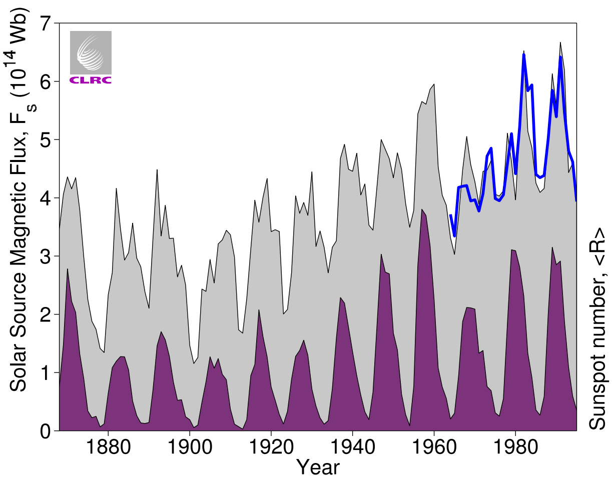

Figure 2. This figure shows estimates back to 1868 of the total solar magnetic flux emanating through the coronal source sphere. (Figure 3 in Lockwood M, Stamper R and Wild M N 1999 A doubling of the Sun's coronal magnetic field during the past 100 years *Nature* **399** 437.)

received from the Sun was believed to be constant, as the term 'SOLAR CONSTANT' for this value indicates. However, in astronomical terms the Sun is a variable star. This has been known for many centuries during which scientists have performed systematic observations of the Sun's surface. The observations demonstrate periodic variations on different time scales. Most pronounced among these is the nearly 11 yr cycle in the number of SUNSPOTS (see also SOLAR CYCLE). Direct indices for solar activity are not really available before the start of the use of telescopes around 1610. However, recently a promising tool has been developed which may enable us to derive indices of solar activity on much longer time scales. This method is based on indirect proxies, for example the cosmogenic radionuclides ^{14}C and ^{10}Be. These nuclides are caused by cosmic ray particles and, because they are electrically charged, both the geomagnetic field and the magnetic field in the heliosphere modulate their production rate. The magnetic field in the heliosphere has its origin in the solar surface magnetic activity. Therefore the inferred production rate of radionuclides in the atmosphere may be used to provide an index of solar magnetic activity back in time (see SOLAR ACTIVITY: LONG-TERM RECORDS).

Such estimates of solar activity variations in the past have made it possible to examine a possible relationship with past climate. A number of studies showing a striking correlation have been reported. During the last millennium the major historically recorded deviations from the present climate are the Medieval warm period during the 11th and 12th centuries, when the Vikings settled in Greenland, and the cool period in Greenland and Europe in the 17th century known as 'the Little Ice Age'. The warm period is associated with a period of high solar activity as deduced from the estimated very low production of radionuclides. On the contrary, the Little Ice Age is associated with a prominent minimum in solar activity, known as the Maunder minimum, during which the production of radionuclides was very high.

The occurrence of sunspots indicates only one manifestation of solar activity. However, it is by no way obvious that the sunspot number is the most relevant parameter for a possible direct effect on climate. Another index of solar activity is the duration of the solar cycle. On the average a solar cycle is about 11 yr but high-activity cycles are generally shorter whereas solar cycles with low peak activity are longer. During this century solar cycles were long at the beginning of the century whereas they were short at the end. In figure 1 the change in solar cycle length during the last 130 yr is compared with the 11 yr running average of the northern hemisphere land temperature. The striking similarity between the two curves indicates that the Sun may have played a major role in global temperature change during this century.

Possible physical mechanisms for solar activity induced effects on climate

In order to claim a direct cause-and-effect relationship it is necessary to point at a plausible physical mechanism. An obvious candidate is the possibility that the total solar irradiance (the solar 'constant') varies in accord with solar activity. Accurate observations of the total irradiance are not possible from the ground because variations in the atmospheric composition by far dominate any changes that might be attributed to variations in the solar 'constant'. It was therefore not until direct measurements from satellites became available in the 1980s that the hypothesis of a solar cycle variation in total irradiance could be tested. These measurements did in fact demonstrate that changes exist, both on short time scales (days to weeks) and on longer time scales (decades). The competing effects of sunspot darkening and faculae brightening could account for the short-term variations. The variations on the decadal time scale did unambiguously show a variation in phase with the sunspot cycle but these variations only amounted to 0.1% between sunspot maximum and sunspot minimum.

The effect on the global temperature of such a change is, however, small compared with other radiative climate forcing parameters associated with changes in the composition of the atmosphere. Even if changes in total irradiance may amount to ∼0.25% over longer periods as has been suggested to be the case for the Maunder minimum, they may only be of minor importance for climate. Whereas the global warming during this century could be mainly due to the enhanced greenhouse effect this cannot be the case for the significant past climate variations. Since many of the past climate changes have been demonstrated to be correlated with changes in solar activity variations, people have looked for indirect mechanisms by which solar activity variations could modulate climate.

One possibility concerns the ultraviolet part of the solar irradiance. Solar cycle variations in this spectral band are much larger than for the visible light. Attempts have therefore been made to model the climatic effect of solar cycle variations taking into account also the modulating effect of the varying ultraviolet radiation on the lower stratospheric ozone. The models show an increased tropospheric Hadley circulation during high solar activity consistent with observations, although the observations also indicate a larger effect than the models predict. The effect may contribute to the observed very clear solar cycle signature in the height of constant pressure levels in the stratosphere, seen consistently during the last four solar cycles in particular between 20°N and 45°N in the Pacific–Atlantic area.

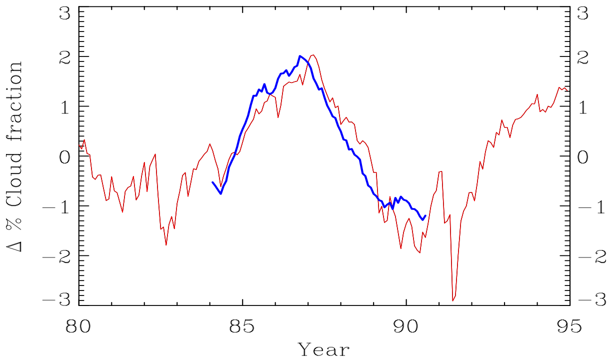

Figure 4. Variation of total cloud cover and cosmic ray flux observed at Climax. (Figure taken from Svensmark H and Friis-Christensen E 1997 Variation of cosmic ray flux and global cloud coverage—a missing link in solar–climate relationships *J. Atmos. Sol.-Terr. Phys.* **59** 1225–32.)

Even more pronounced manifestations of solar cycle effects in the solar energy output are associated with the solar wind, the emission of particles and fields from the solar surface. Although the energy in the solar wind is negligible compared with the energy in the ultraviolet and visible spectral bands, the relative variations are much larger. A direct effect of the varying solar wind is seen in the fluctuations in the geomagnetic field due to electric currents in the magnetosphere and the ionosphere. The *aa* index has been derived from such fluctuations recorded at two geomagnetic observatories in England and Australia since 1868. From the time series of this index it has been inferred the total magnetic field leaving the Sun may have increased by a factor of more than 2 during this century (see figure 2). Such an increase is most likely the cause of the decreasing cosmic ray flux during this century, which has been observed from the ground since the 1930s and which has also been inferred from the ^{10}Be data from ice cores in Greenland. Figure 3 shows the cosmic ray flux observed at the Climax Neutron Monitor station in Colorado. Note the reversed scale indicating a clear solar cycle modulation nearly in antiphase with the variation of the sunspot number, R. The figure also shows the geomagnetic activity index, *aa*, which has a solar cycle variation quite different from the sunspot cycle.

One of the major uncertainties in climate models is the role of clouds (see also CLOUDS IN PLANETARY ATMOSPHERES). In particular there are large difficulties associated with the parameterization of these effects in general circulation models used in climate studies. Recent studies indicate that cloud formation may be influenced by Galactic cosmic rays through ionization changes that cause microphysical changes in the atmosphere. Hereby nucleation and growth of ice particles may be affected.

A change in cloud cover would indeed be a very effective amplifying mechanism for climate forcing because the energy necessary to condense water vapor is small compared with the resulting changes in energy of solar radiation received at the Earth's surface. Figure 4 shows the result of an examination of the compiled International Satellite Cloud Climatology Project (ISCCP) data. The 12 months running mean of the total cloud cover (thick curve) is shown together with the 12 months running mean values of cosmic ray intensity measured at the Climax Neutron Monitor station, Colorado. The correlation between the cosmic ray flux and the global cloud cover is very high and indicates a direct relationship although a detailed mechanism is still lacking.

Summary

The Earth's climate is a very complex system with a number of elements and with many feedback mechanisms. Various processes including variations in solar activity can cause climate changes. The detailed mechanisms and the relative importance of the different processes are still not very well known but increased understanding of our environment including the processes on the solar surface and in the heliosphere will considerably improve our ability to estimate the effect on climate of human activity.

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